Simulations of particle beam heating of foils for studies of warm dense matter*

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Abstract

We present simulations of particle beam heating of target foils using the multi-physics radiation hydrodynamics code HYDRA**. We simulate possible targets for a near-term experiment at LBNL (the so-called Neutralized Drift Compression Experiment, NDCX) and possible later experiments on a proposed facility (NDCX-II) for studies of warm dense matter. Simulation results are presented showing the degree of temperature uniformity and the maximum temperature expected. Various target materials (including aluminum, aluminum foam, water ice, and gas jets) and target configurations are presented. Strategies for characterizing the material equation of state, using data from the experiments together with simulations, will be discussed. Requirements on the NDCX-II accelerator, based on target considerations, will also be discussed.

**M. M. Marinak, G. D. Kerbel, N. A. Gentile, O. Jones, D. Munro, S. Pollaine, T. R. Dittrich, and S. W. Haan, Phys. Plasmas 8, 2275 (2001).

Outline of poster

1. Motivation for accelerator driven Warm Dense Matter studies

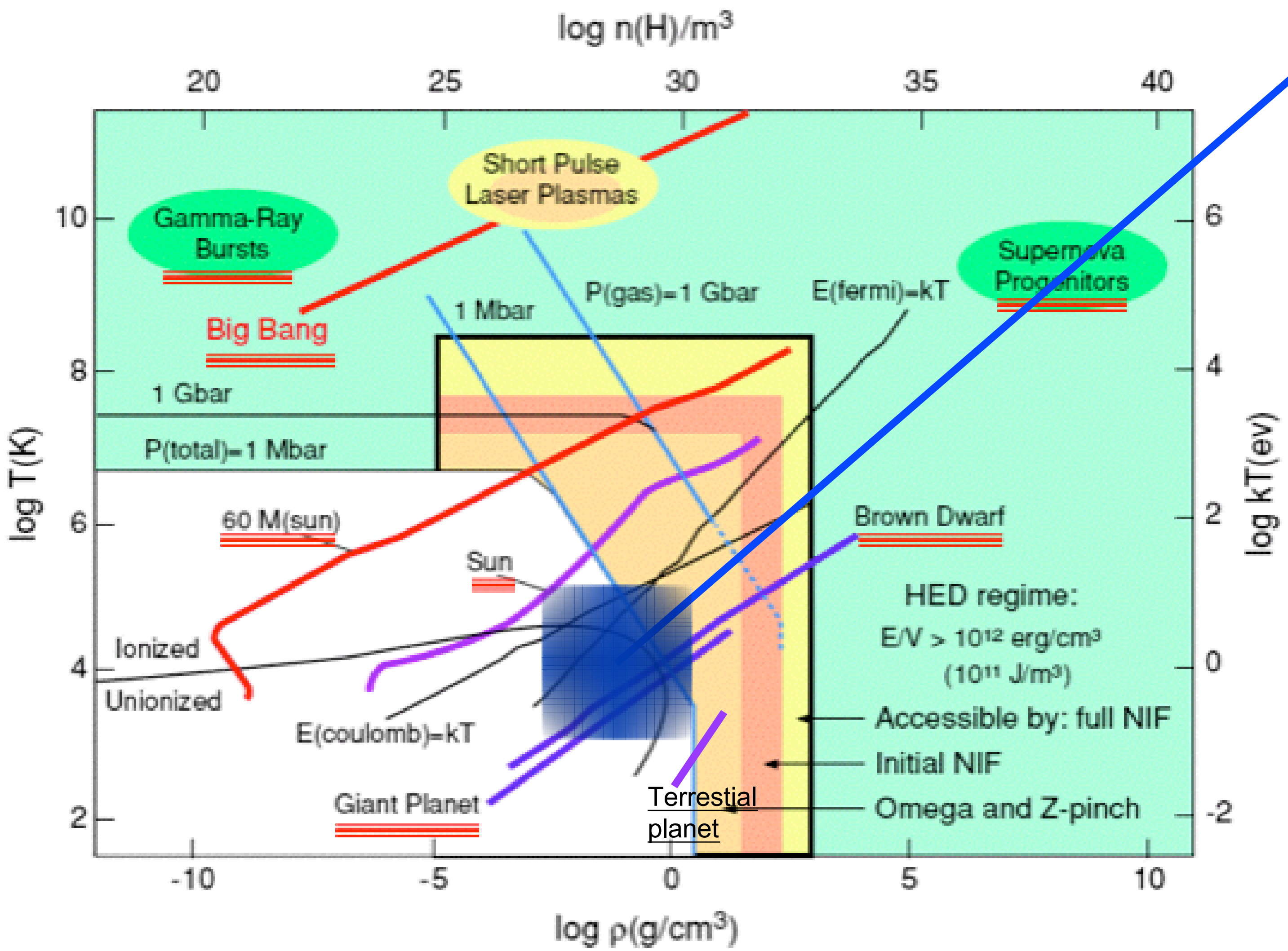
2. Parameters of current and proposed accelerators

3. Simulations of target experiments

    -- Validation of uniformity
    -- Explorations of two-phase regime
        Existence of temperature/density “plateaus”
    -- Rayleigh-Taylor instability using ion deposition
    -- Other experiments

The ρ - T regime accessible by beam driven experiments lies square in the interiors of gas planets and low mass stars

Figure adapted from "Frontiers in HEDP: the X-Games of Contemporary Science:"



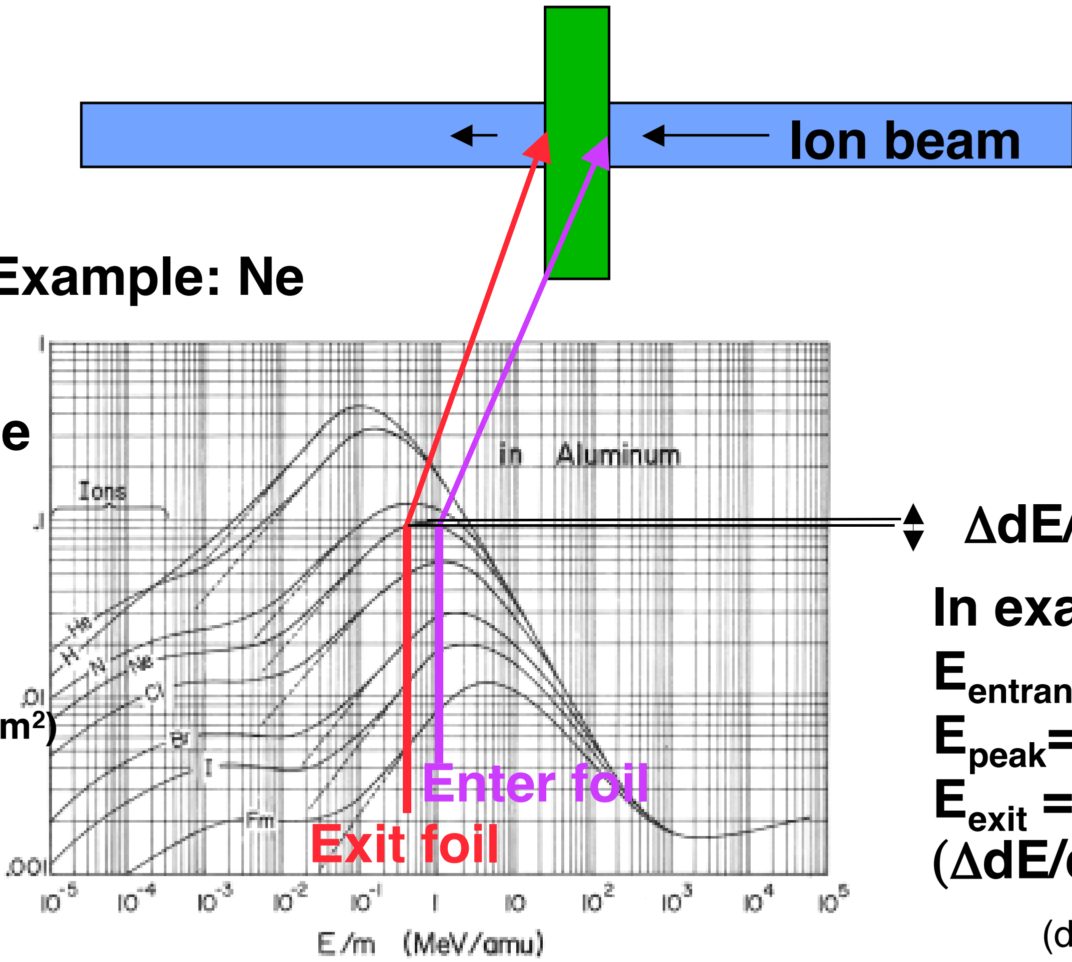
Accessible region using beams in near term

Region is part of Warm Dense Matter (WDM) regime

WDM lies at crossroads of degenerate vs. classical and strongly coupled vs. weakly coupled

Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak

In simplest example, target is a foil of solid or "foam" metal



Energy loss rate

$$-\frac{1}{Z^2}\frac{dE}{dX}$$

(MeV/mg cm²)

Energy/Ion mass **(MeV/amu)**

fractional energy loss can be high and uniformity also high if operate at Bragg peak (Larry Grisham, PPPL)

$\Delta dE/dX \propto \Delta T$

In example,
$E_{entrance}$=1.0 MeV/amu
E_{peak}= 0.6 MeV/amu
E_{exit} = 0.4 MeV/amu
$(\Delta dE/dX)/(dE/dX) \approx 0.05$

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970))

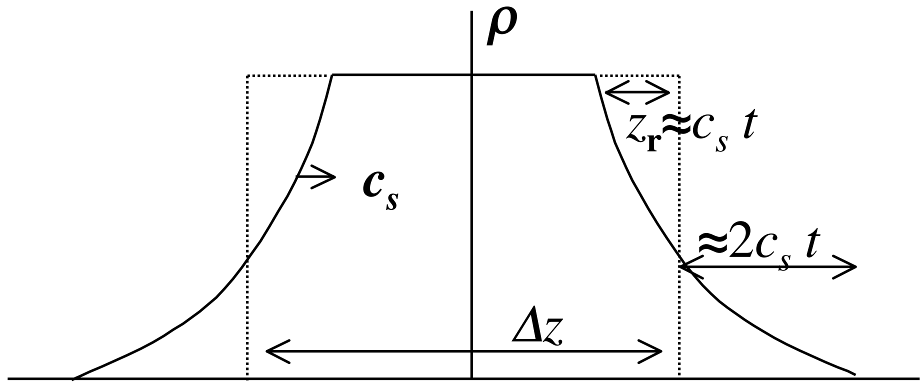
Pulse duration must be short to avoid hydrodynamic expansion and cooling

$$\tau_{\text{pulse}} < z_r/c_s$$

Here: τ_{pulse} **= pulse duration**

z_{r} **= distance, such that diagnosable portion of heated target remains**

c_{s} **= sound speed**



Rarefaction wave propagates inward at c_s (with c_s increasing with time)

The heating pulse should be delivered in a time short compared to the time it takes for a rarefaction wave to reach an interior point, such that a significant portion of the target has reached maximum temperature.

Basic Requirements

Temperature T > ~ 1 eV to study Warm Dense Matter regime

Mass Density ρ ~ 0.01 to 1.0 times solid density

Strong coupling constant Γ ~ 1

For isochoric heating: Δt must be short enough to avoid cooling from hydrodynamic expansion

Uniformity: $\Delta T/T$ < ~5% (to distinguish various equations of state)

Low accelerator cost is a strong consideration, in present environment

A user facility for ion beam driven HEDP will have unique characteristics

Precise control of energy deposition

Uniformity of energy deposition

Large sample sizes compared to diagnostic resolution volumes

Relatively long times allow equilibrium conditions

A benign environment for diagnostics

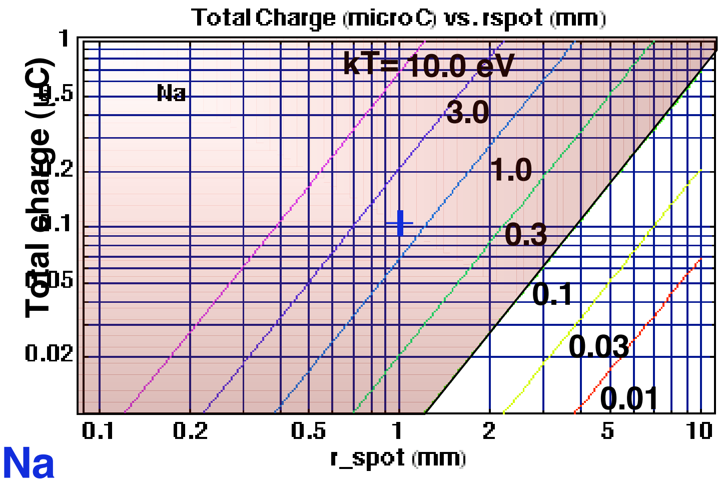
High shot rates (10/hour to 1/second) (simple targets and high accelerator rep rates)

Various ion masses and energies have been considered for Bragg-peak heating

Beam parameters needed to create a 10 eV plasma in 10% solid aluminum foam, for various ions (10 eV is equivalent to ~ 10^{11} J/m^3 in 10% solid aluminum)

Beam Ion	Z	A (amu)	Energy at Bragg Peak (MeV)	dE/dX at Bragg Peak (MeV-cm2/mg)	Foil Entrance Energy (app) (MeV)	Delta z for 5% T variation (10% solid Al) (microns)	Beam Energy for 10 eV (J/mm2)	t_hydro= delta z/(2 cs) at 10 eV (ns)	Beam Power per sq. mm (GW/mm2)	Beam current for 1 mm diameter spot (A)
Li	3	6.94	1.6	2.68	2.4	22.1	3.3	0.5	6.1	1990.6
Na	11	22.99	15.9	11	23.9	53.5	8.0	1.3	6.1	200.3
K	19	39.10	45.6	18.6	68.4	90.8	13.6	2.2	6.1	69.8
Rb	37	85.47	158.0	39.1	237.0	149.7	22.4	3.7	6.1	20.2
Cs	55	132.91	304.0	59.2	456.0	190.2	28.5	4.7	6.1	10.5

The parameters for a Neutralized Drift Compression Experiment (NDCX II) are chosen to heat target to reach WDM conditions



Na

Z=11; A=22.99

$E_{center\ of\ foil}$= 15.7 MeV

$E_{foil\ entrance}$ = 23.5 MeV (β =0.047)

dE/dX = 10.13 MeV cm^2/mg

Z = 5.75 μ (ρ_{al}/ρ)

U= 8.7 x 10^{10} J/m^3 $(1mm/r)^2$ (q_{tot}/0.1μC)(ρ/ρ_{al})

kT= 1.5 eV $(1mm/r)^2$(q_{tot}/0.1μC)

Target requirements set specifications for beam phase space at end of accelerator (and hence at injector)

- **Longitudinal velocity spread limits pulse duration**
- **Emittance and chromatic aberrations limit spot radius**
- **Large velocity tilt allows shorter pulses but adds to chromatic aberration**

Without adiabatic lens:

$\Delta v/v$_tilt= 0.05

ε_N <= 2.3 mm-mrad

$\delta p/p$_rms = 0.2 %

(at 1 MV, 177 ns injector)

Tradeoffs for compression factor of 20 and 1 mm final spot radius:

Velocity tilt (Head to tail) dv/v_tilt	Maximum rms velocity spread dp/p_rms (befor drift comp)	Maximum emittance unnormalized 4 rms (mm-mrad)	Maximum normalized emittance 4 rms (mm-mrad)	Beam radius at solenoid entrance Ro (m)	Neutralized Drift length (m)	Maximum rms velocity spread dp/p_rms (at injector)
0.05	7.22E-04	49.5	2.3	0.031	5.34	1.98E-03
0.1	1.44E-03	24.7	1.2	0.016	2.67	3.97E-03
0.2	2.89E-03	12.4	0.6	0.008	1.34	7.93E-03

Parameters of experiments in the NDC sequence leading to a user facility (IBX/NDC)

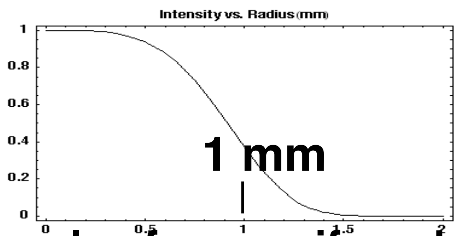
	Existing machine, 1 year goal	**3 - 5 year goal**		**10 year goal**	
	NDCX-I	NDCX-II		NDCX-III (IBX-NDC)	
Ion Species	K^+	Na^+	Li^+	Na^+	Li^+
Total Charge (μC)	0.002	0.1	0.3	0.3-1.0	1.0
Final Ion Energy (MV)	0.4	23.5	2.4	23.5	2.4
Final Pulse Duration (ns)	2	1	1	1	1
Final Spot Radius (mm)	0.5-1.0	1	1	1	1
Total pulse energy (J)	0.0008	2.4	0.72	7.1-24	2.4
Expected Target Temp (eV)	0.05 - 0.1	2 - 3	1 - 2	5-10	3

NDCX = neutralized drift compression experiment
IBX = integrated beam experiment

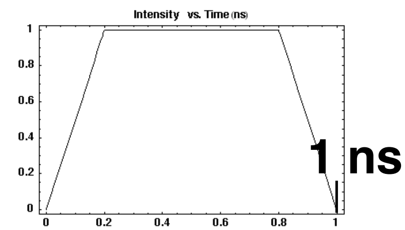
We have begun using the 3D LLNL code HYDRA for our target studies

-- A state-of-the-art multi-physics radiation transport/ hydrodynamics code by M. Marinak et al[1]
-- Initial explorations of ion beam interactions with foil targets[2]:

Power vs. radius:

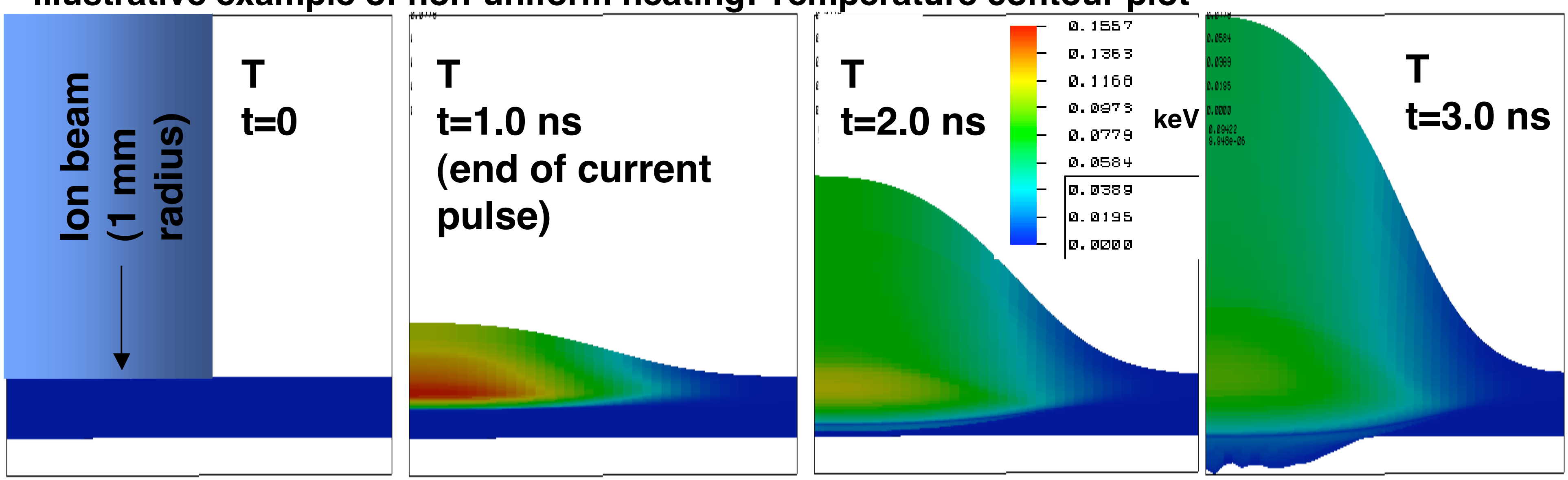


Power vs. time:



20 MeV Ne beam hitting 10% Al foam foil

Illustrative example of non-uniform heating: Temperature contour plot

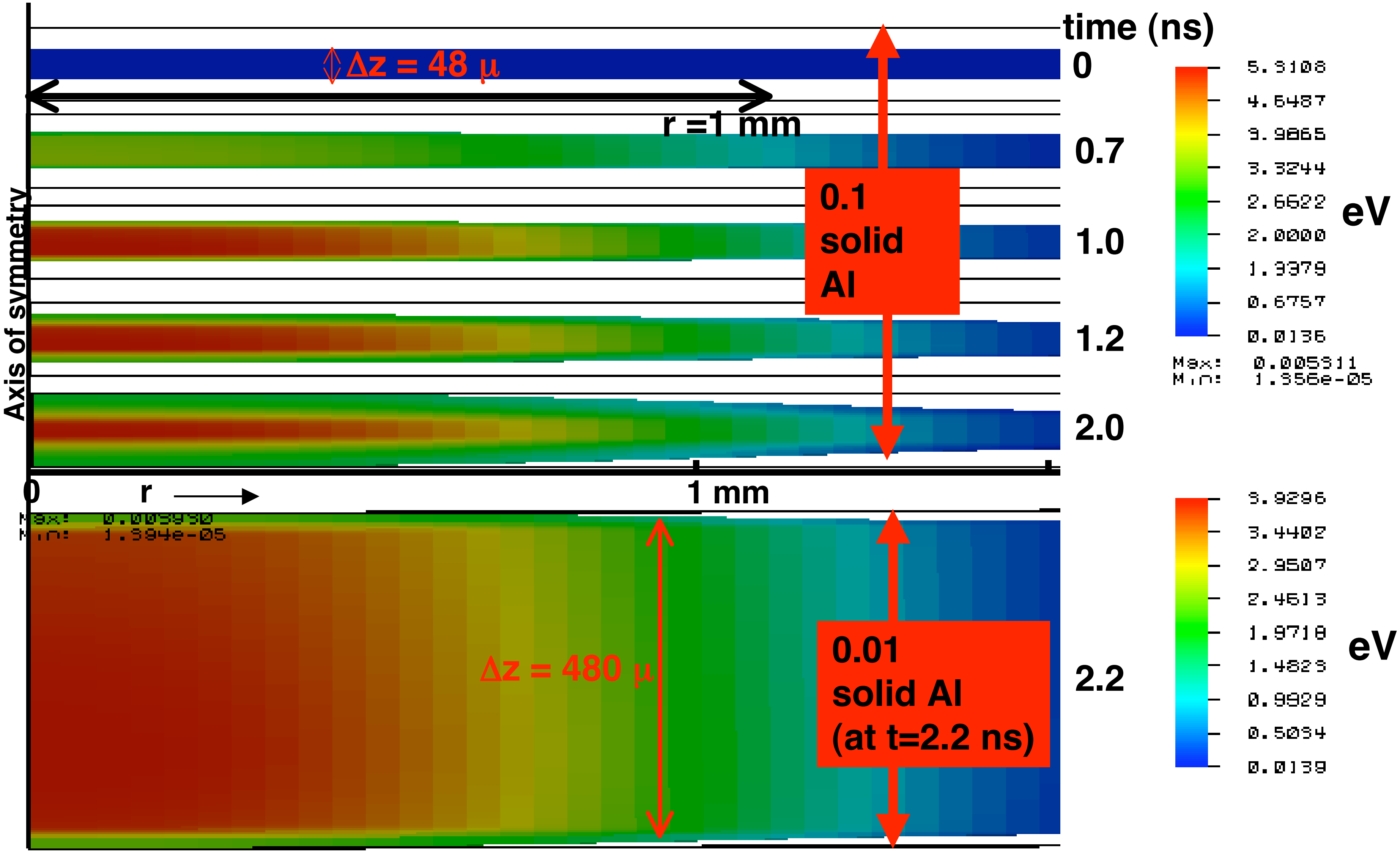


r=0 $r=r_b$

(2D [r-z], time-dependent simulations; Intensity 100 x higher, foil 3 x thicker for demo only)

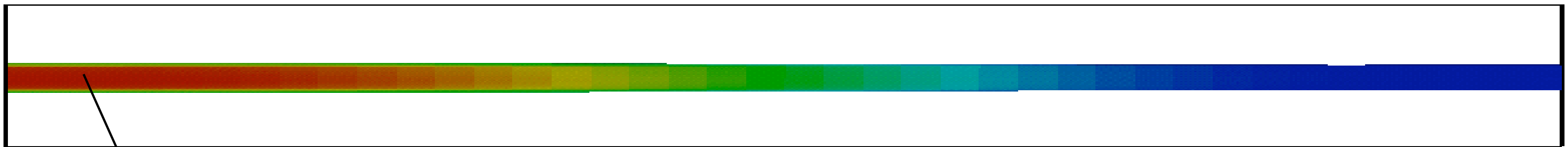
1. M. M. Marinak, G. D. Kerbel, N. A. Gentile, O. Jones, D. Munro, S. Pollaine, T. R. Dittrich, and S. W. Haan, Phys. Plasmas 8, 2275 (2001).
2. Simulation collaborators: J.J. Barnard, G.E. Penn, J. S. Wurtele, P. Santhanam, A. Friedman, M. M. Marinak

Initial Hydra simulations confirm temperature uniformity of targets at 0.1 and 0.01 times solid density of Aluminum

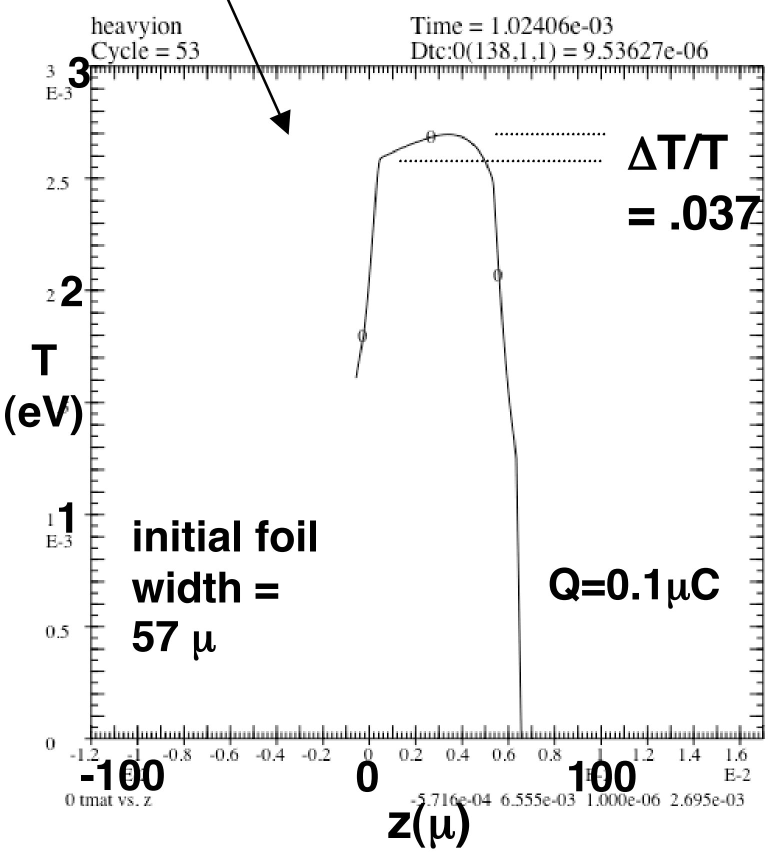


(simulations are for 0.3 μC, 20 MeV Ne beam -- IBX/NDC parameters from workshop).

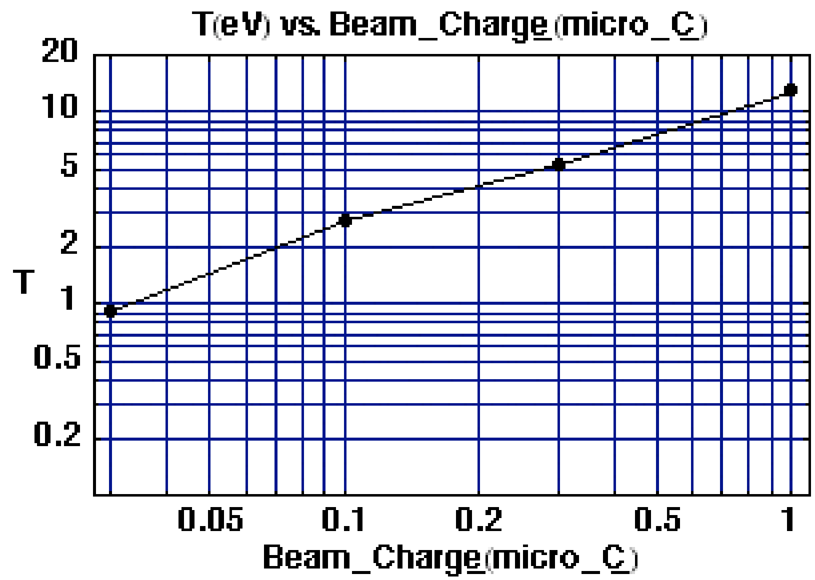
For NDCX-II parameters, temperatures of a few eV could be achieved with high uniformity



t=1ns



Variation of target temperature with total beam charge *Q*



(HYDRA results using QEOS, in Al 10% solid density; 23.5 MeV 1 mm Na^{+} ion beam)

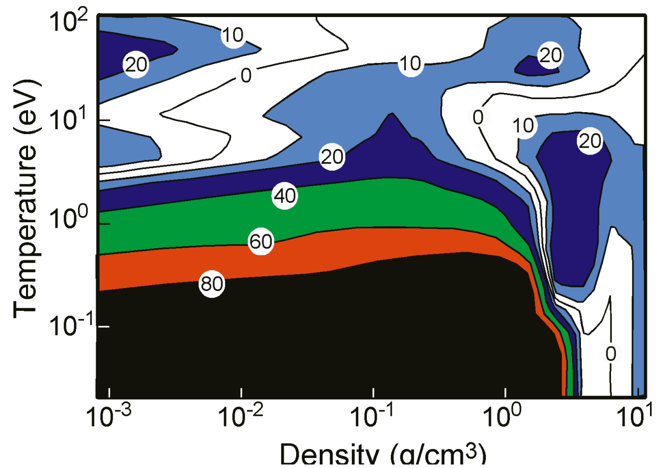
New theoretical EOS work meshes well with experimental capabilities we will be creating

Large uncertainties in WDM region arise in the two phase (liquid-vapor) region

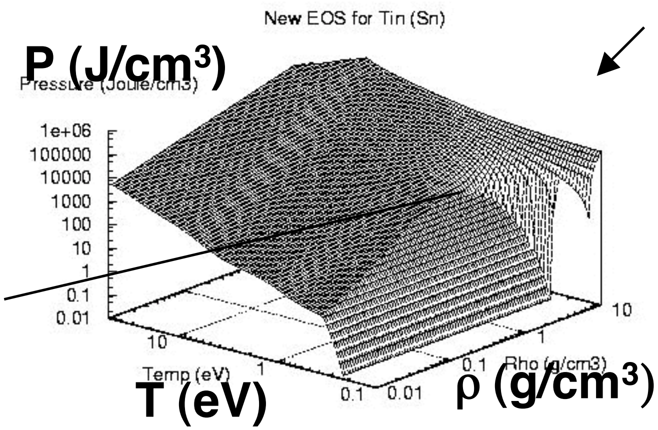
Getting two-phase regime correct will be main job for WDM

R. More has recently developed a new high quality EOS for Sn.

Interesting exactly in the ~1.0 eV regime.



Plot of contours of fractional pressure difference for two common EOS (R. Lee)



Critical point unknown for many metals, such as Sn

New EOS (*cf* R. More, T. Kato, H. Yoneda, 2005, preprint.)

EOS tools for this temperature and density range are just now being developed.

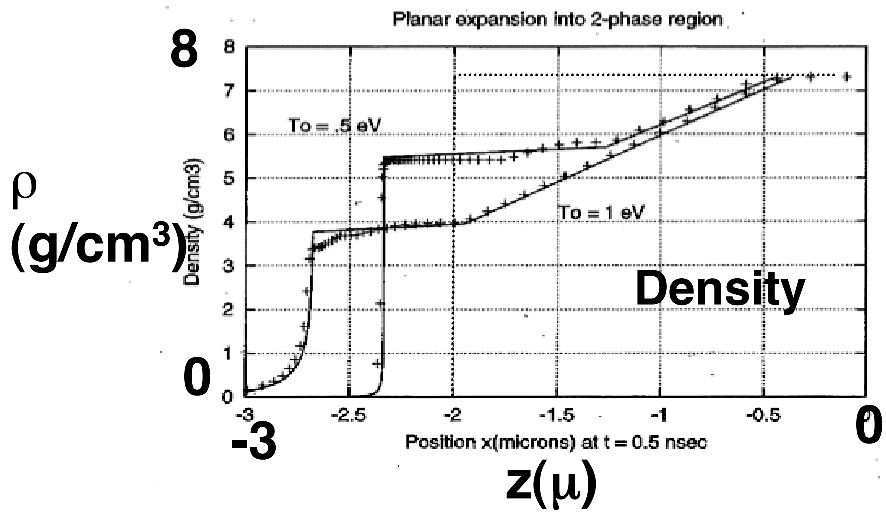
New EOS predicts a sharp density cliff which may facilitate detection and help determine metallic critical points

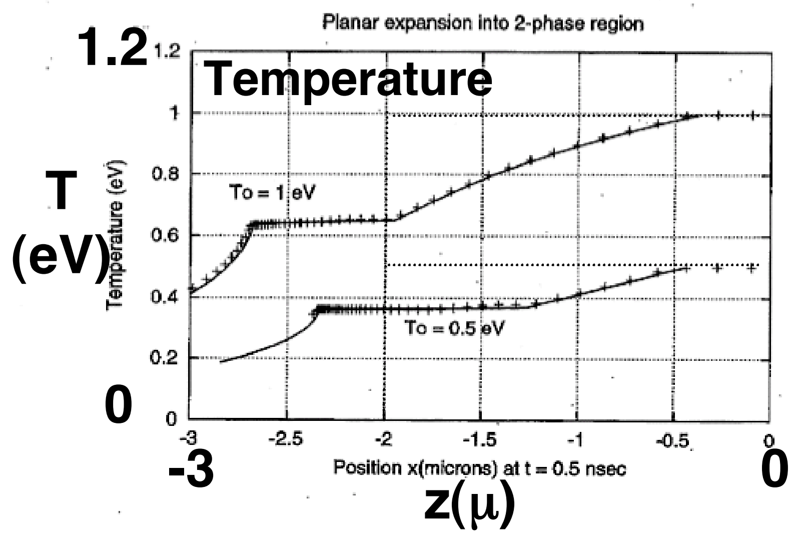
R. More et al[1] have used a new EOS in 1D hydro calculations.

EOS based on known energy levels and Saha equation (in contrast to QEOS, which uses "average" (Thomas Fermi) atom model

Two phase medium results in temperature and density plateaus with cliffs[1,2]

Initial distribution



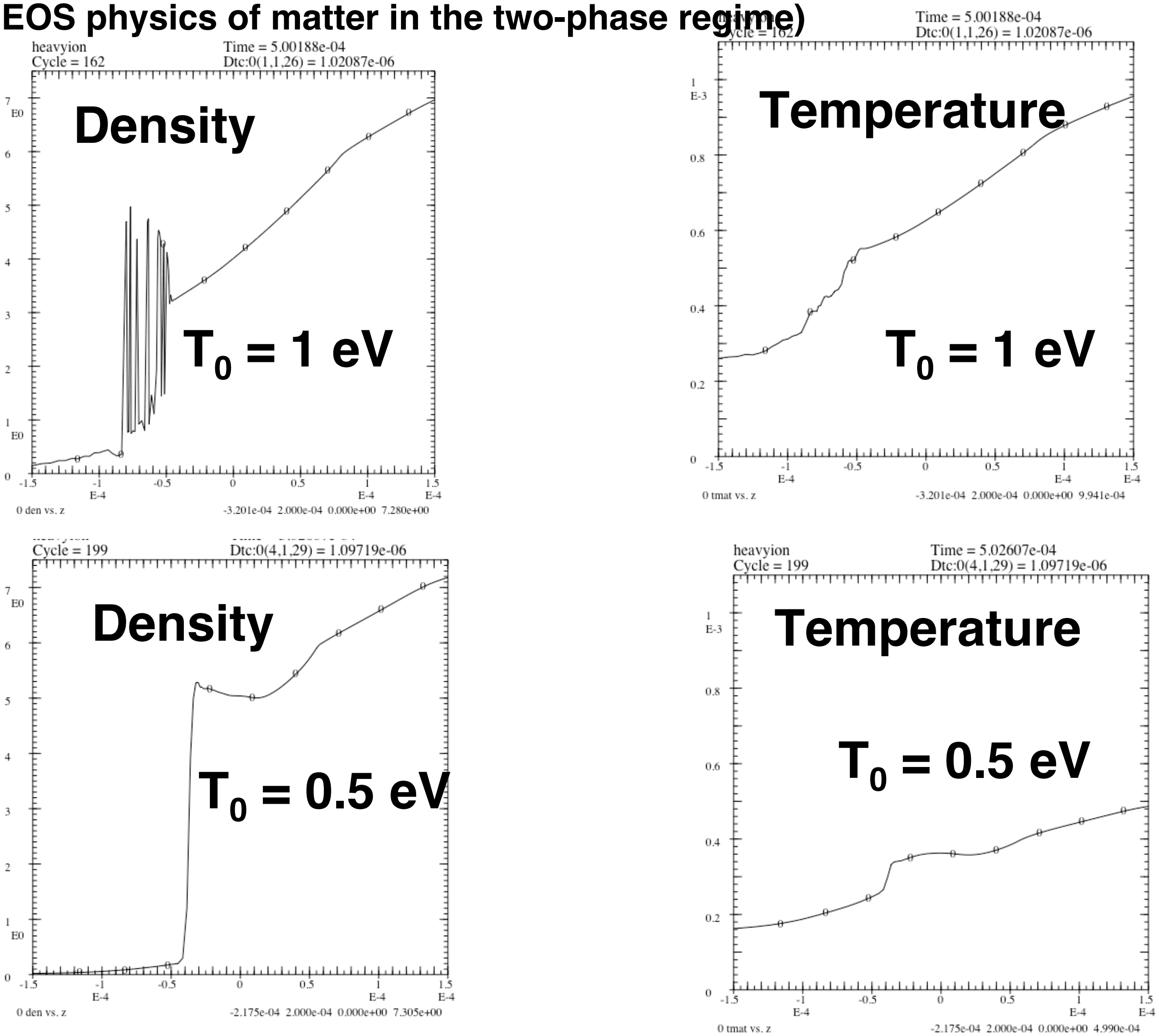


Example, shown here is initialized at T=0.5 or 1.0 eV and shown at 0.5 ns after "heating." Expect phenomena to persist for longer times and distances, but still to be explored.

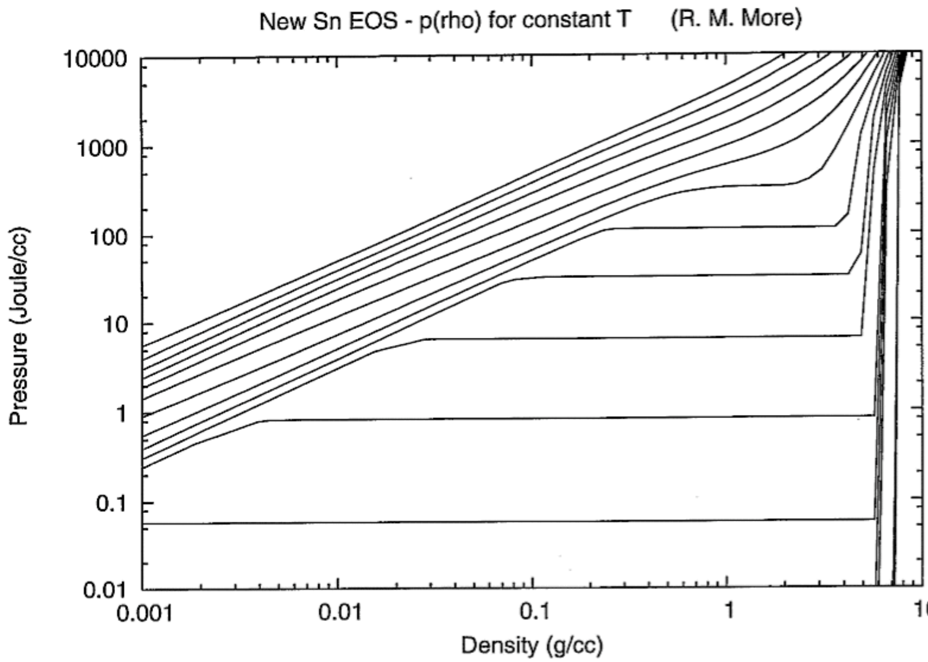
[1]R. More, T. Kato, H. Yoneda, 2005, preprint. [2]Sokolowski-Tinten et al, PRL 81, 224 (1998)

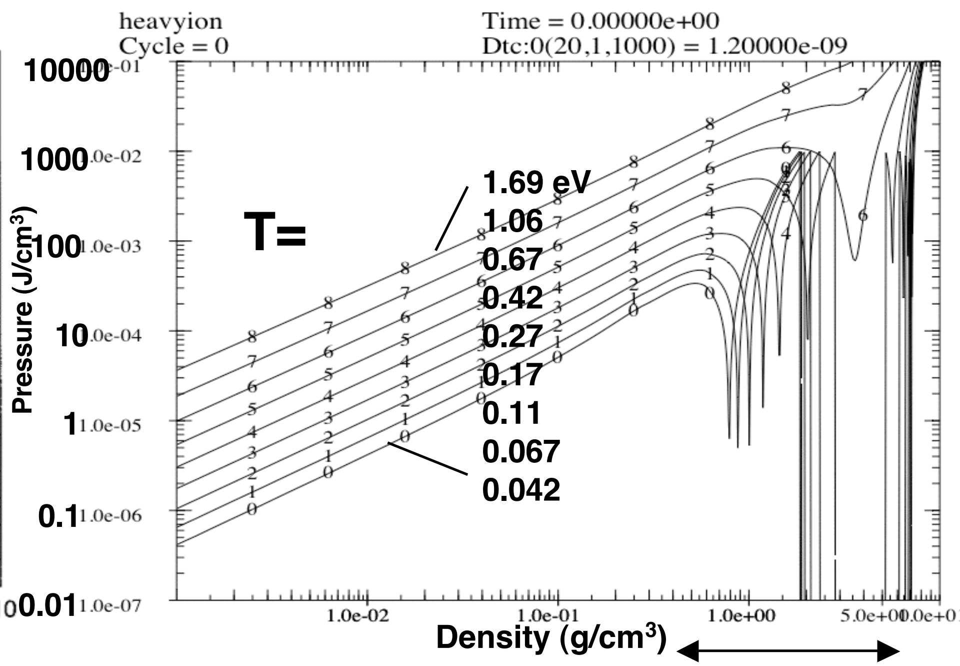
HYDRA simulations show both similarities to and differences with R. More simulation of 0.5 and 1.0 eV Sn at 0.5 ns

(oscillations at phase transition at 1 eV may be due to numerical problems, but is more likely due to the different EOS physics of matter in the two-phase regime)



Differences from HYDRA simulations and R. More simulations are likely due to differences in EOS

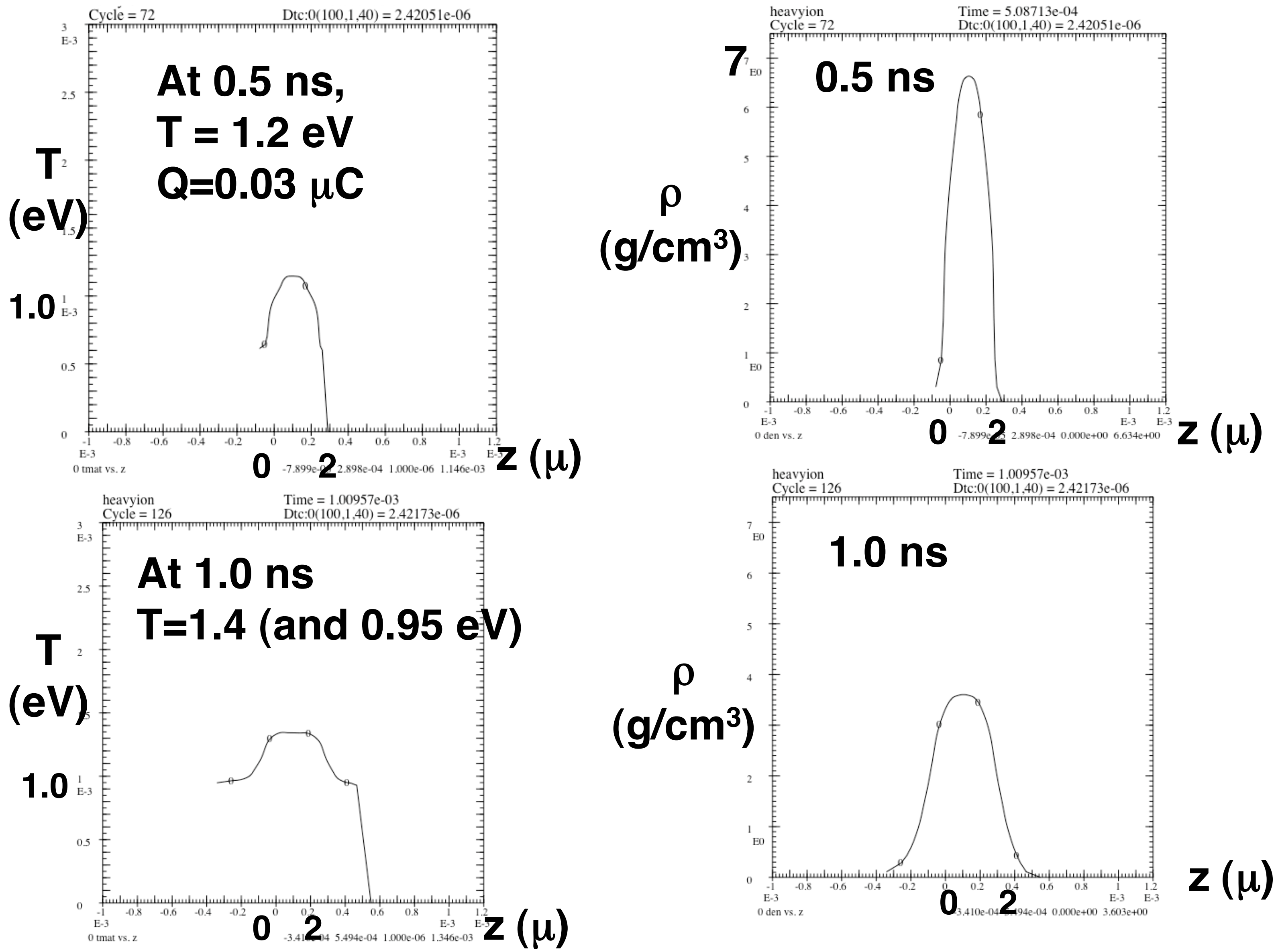




R. More EOS above includes two phase regime, whereby pressure is independent of average density, and material is a combination of liquid and vapor (i.e. bubbles) with microscopic densities at the extreme ends of the constant pressure segment, respectively

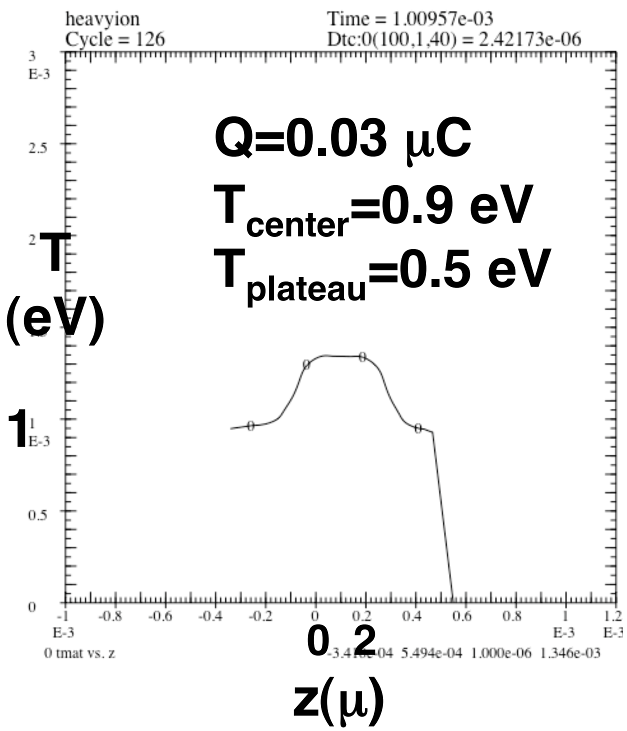
Hydra uses modified QEOS as one of its options. Decreasing ∂P/∂ρ (at fixed T) indicated by arrow results in dynamically unstable material, so EOS becomes better modeled by a two-phase average pressure.

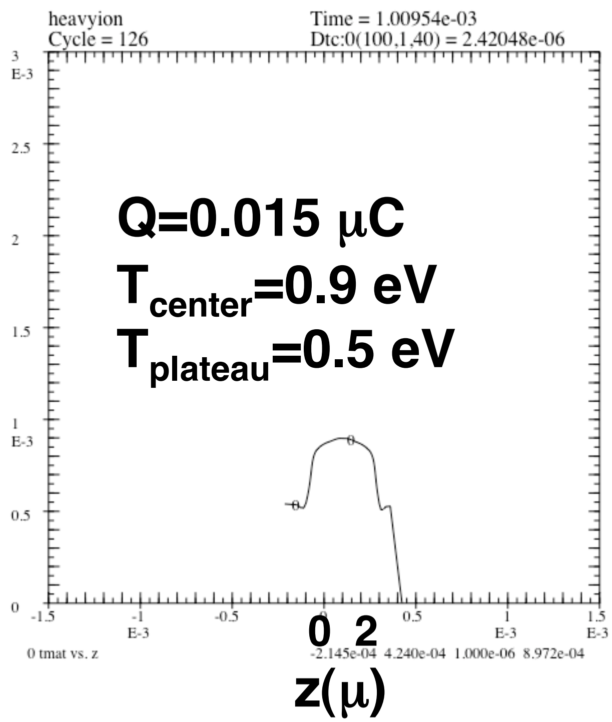
Early explorations using Hydra of beam heating of Sn at solid density to ~1 eV shows evidence of T plateau

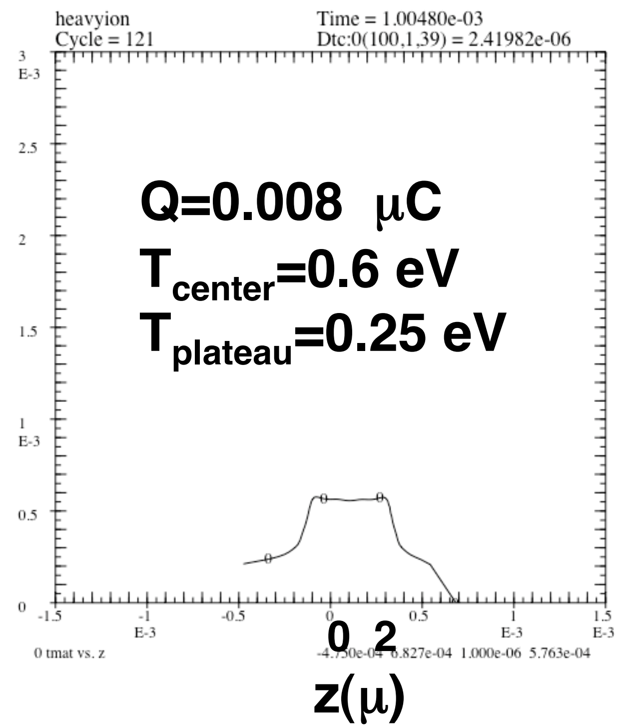


Variation of temperature profiles for 2 μ Sn foil with various beam intensities, shows hints of predicted behavior

All plots are for 23.5 Na beam, after 1 ns

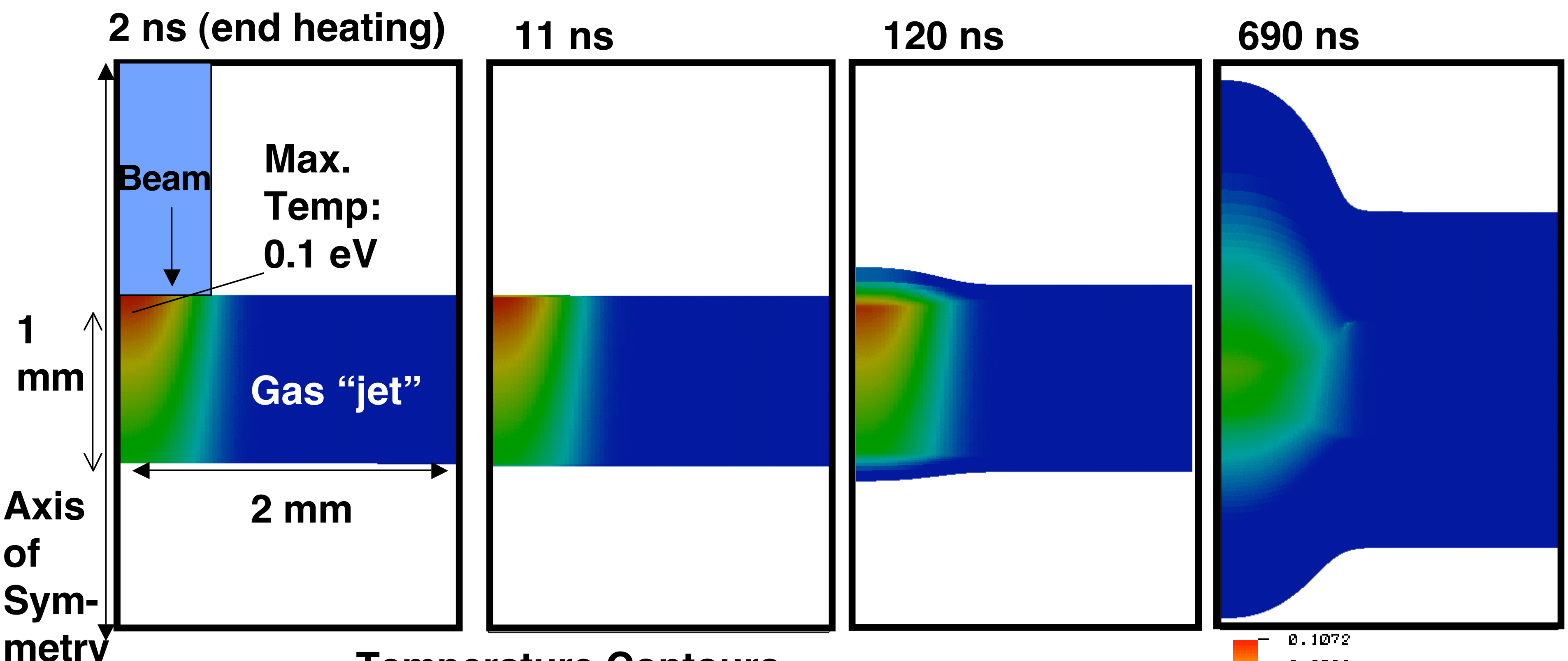




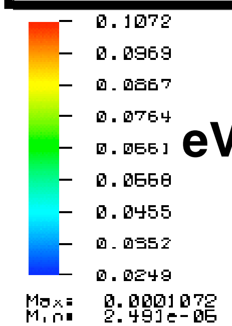


Existence of temperature plateaus appears related to passage of matter through 2-phase medium, but density plateaus not present, perhaps due to finite beam duration or differences in EOS

We have used HYDRA to begin scoping possible near-term experiments on NDCX-I

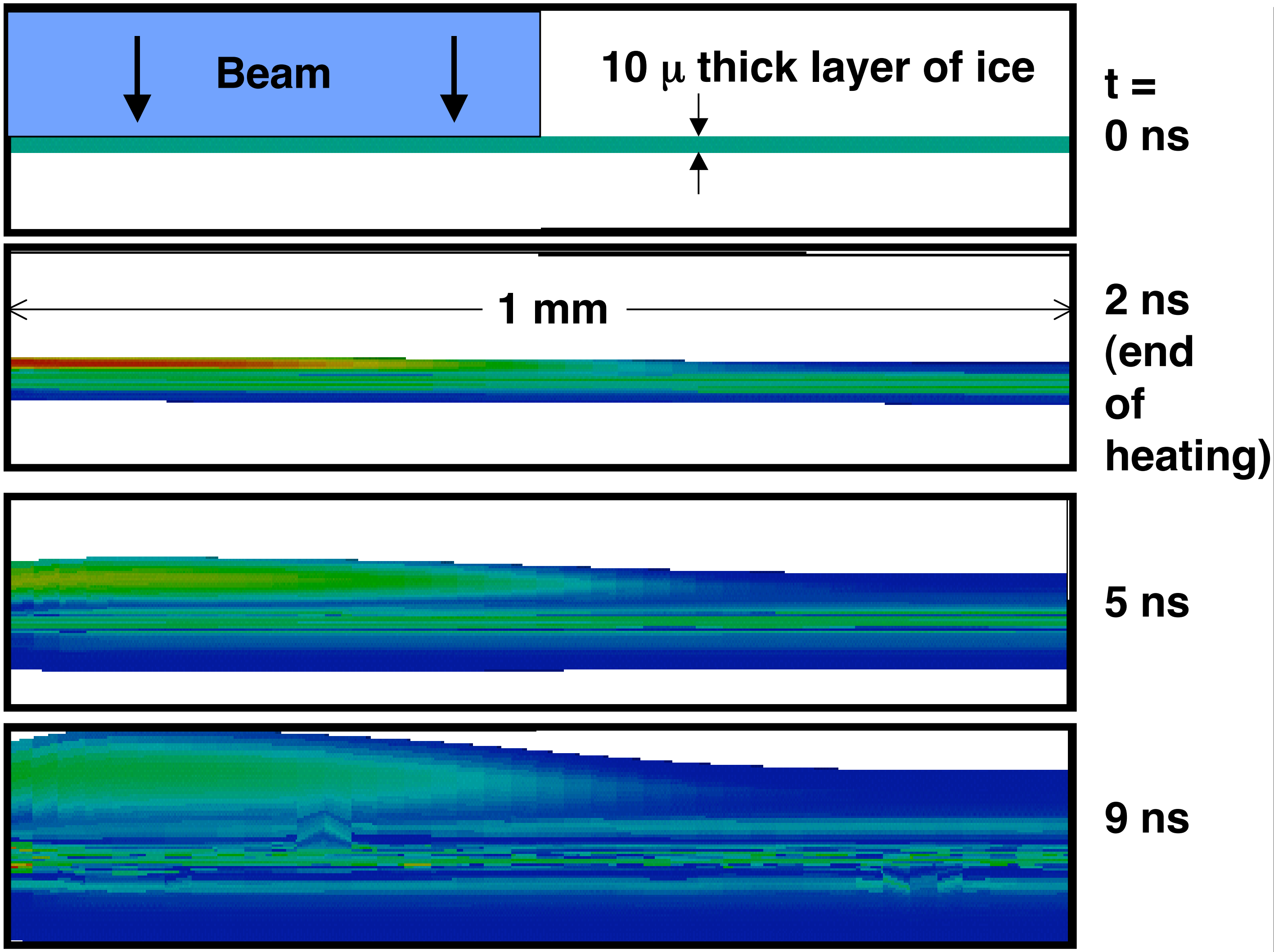


Temperature Contours



Simulation parameters:
Target: 1 mm thick Argon gas "jet" at 1 atmosphere
Beam: 0.5 mm radius, 2 ns, 1A, K^+
(final strong solenoid would be required for 0.5 mm spot)

Other near-term hydro experiments could be carried out with a frozen liquid (such as H_20, iodine, mercury, etc.)



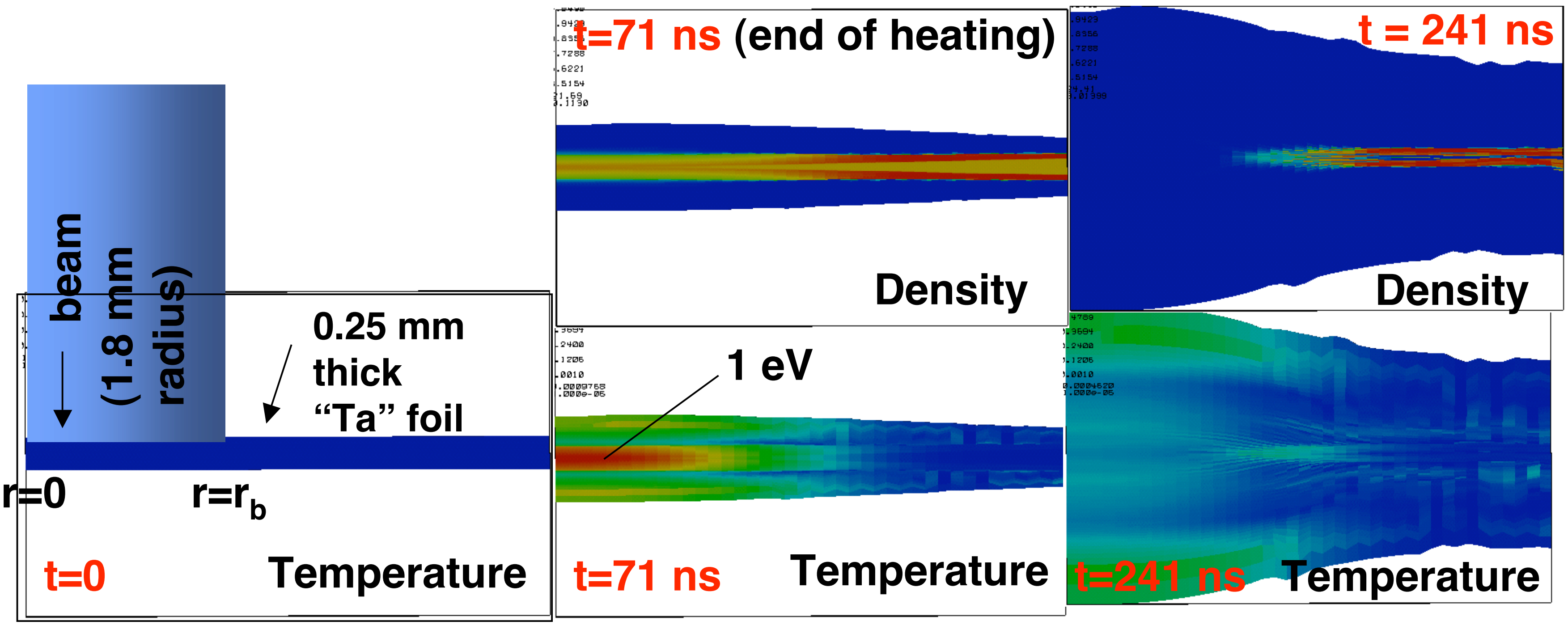
Beam parameters:
0.5 mm radius
1 A K^+
2 ns

Target parameters:
10 μ thick layer of water ice (possibly on top of solid surface--not included in simulation)

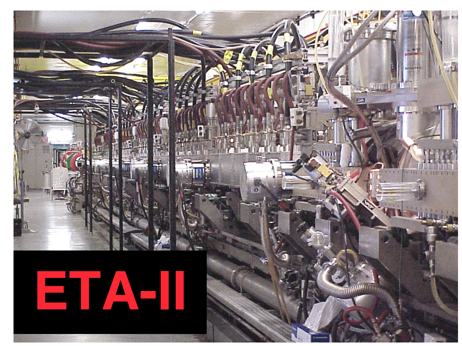
Maximums:
T = 0.07 eV
P=0.027 Mbar = 2.7GPa (at 3 ns)

Target experiments on ETA II, could also provide target experience in interesting regime

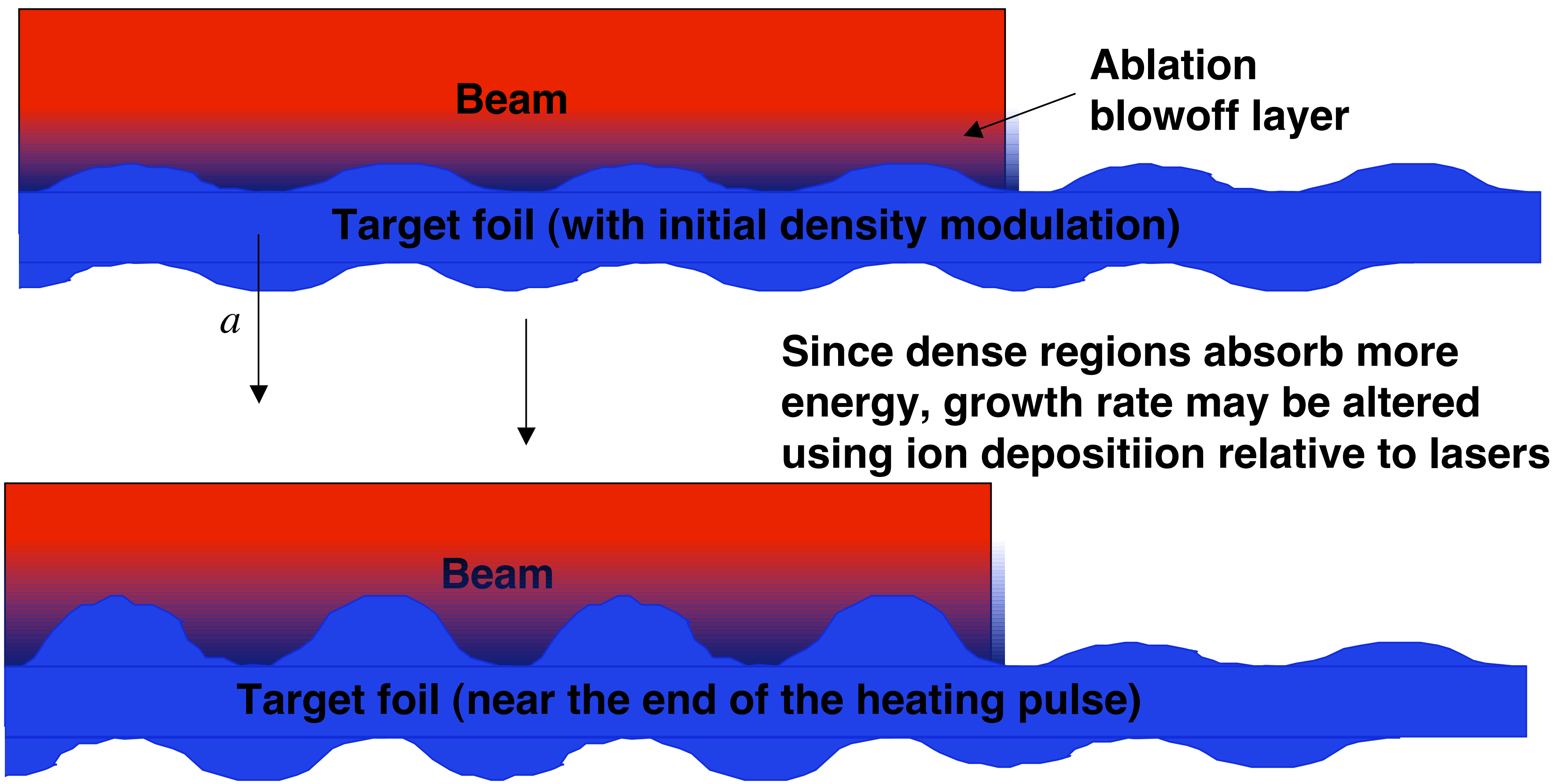
Example: “Tantalum-like” foil, with equivalent 40 GeV proton beam



- ETA II parameters: 5 MeV e-, 2 kA, 50 ns,
- Need to adapt electron beam deposition to include scattering



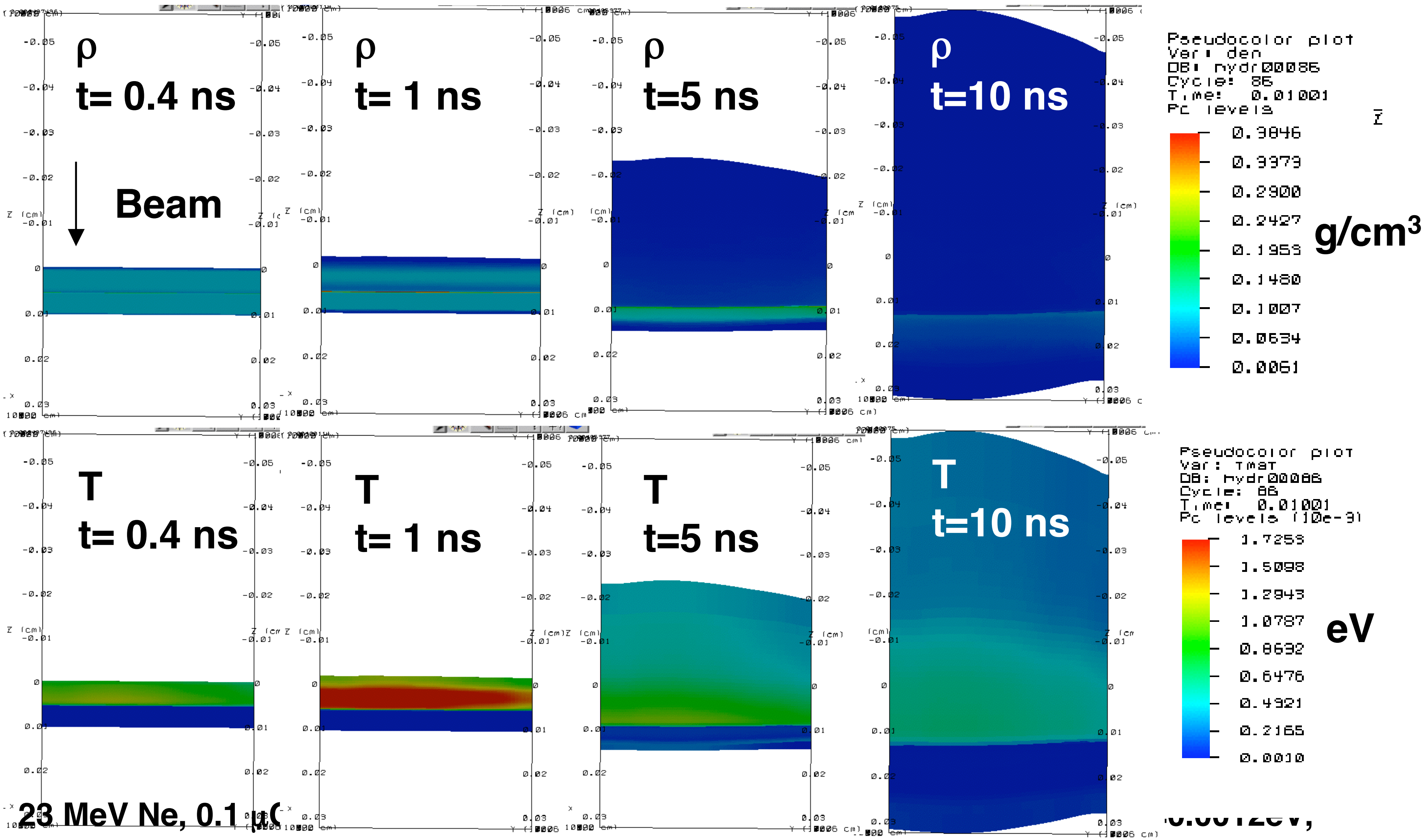
Energy deposition using ion beams may alter the growth rate of the Rayleigh-Taylor instability relative to lasers



Growth rate γ **(for laser deposition)** : $\gamma \approx (k\,a\,/(\,1 + k\,L))^{1/2} - \alpha\,k\,V_a$, **where** k **is the wave number of the perturbation,** a **is the acceleration rate,** L **is the density-gradient scale length,** α **is a constant between** 1 **and** 3, V_a **is the velocity of the ablation front (Lindl, 1998[1])**

1. John D. Lindl,"Inertial Confinement Fusion," Springer-Verlag, NY, 1998

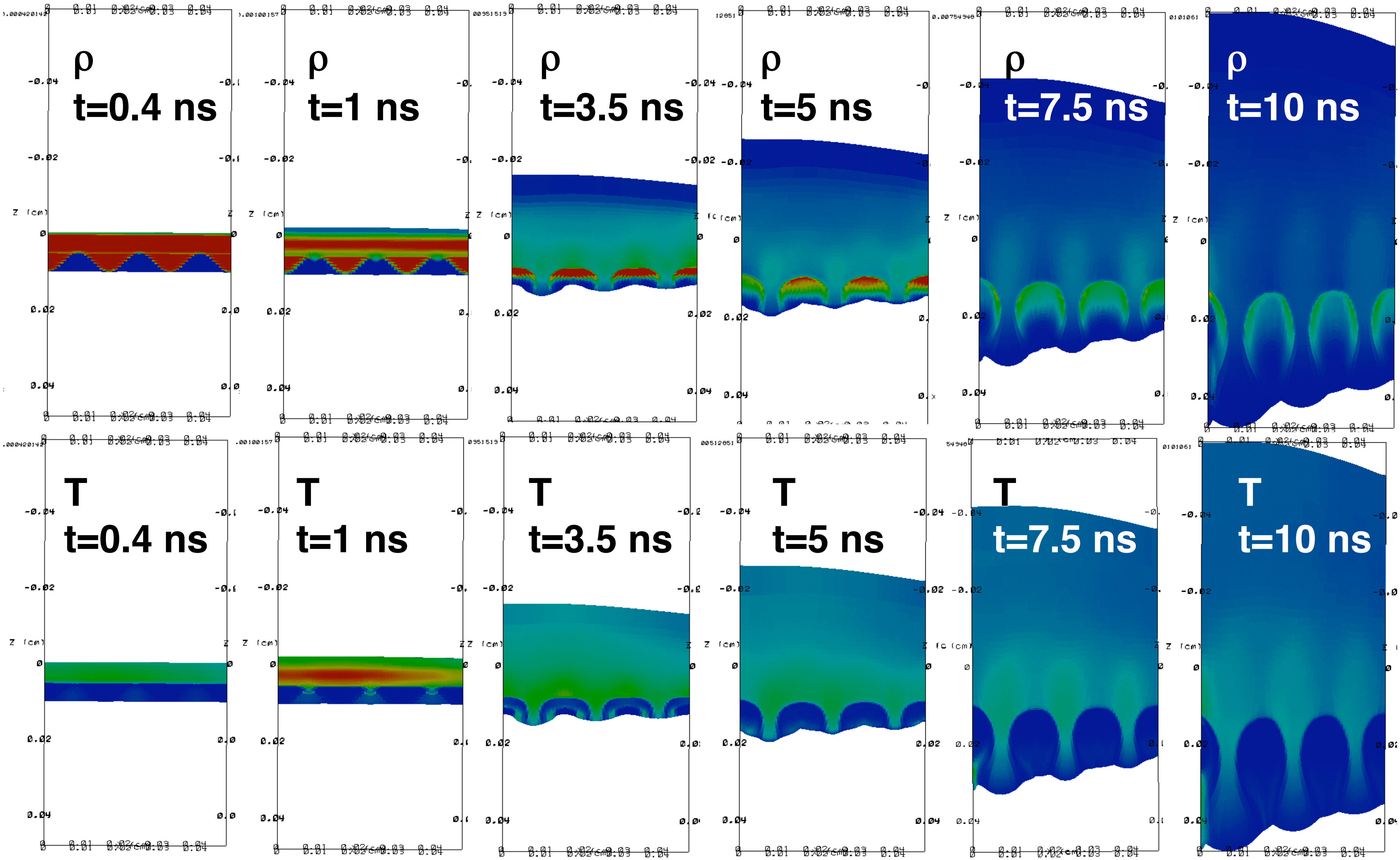
We have begun using Hydra to explore accelerator requirements to study beam driven Rayleigh Taylor instability



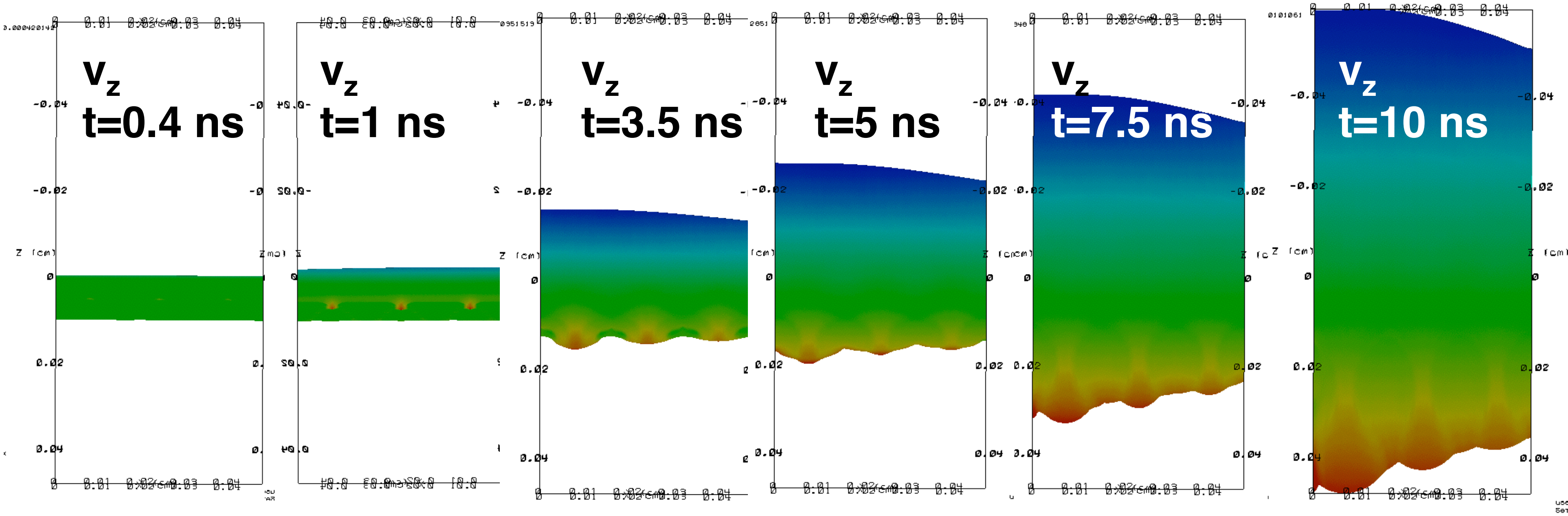
23 MeV Ne, 0.1 μC

ρ =0.088 g/cm3; No density ripple on surface, blowoff accelerates slab

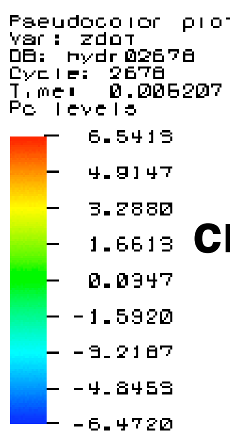
When initial surface ripple is applied, evidence for Rayleigh Taylor instability is suggestive



When initial surface ripple is applied, evidence for Rayleigh Taylor instability is suggestive (-- continued)

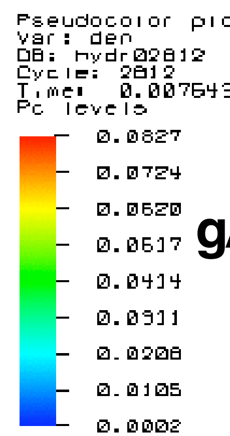


Scale for above figures (v_z):

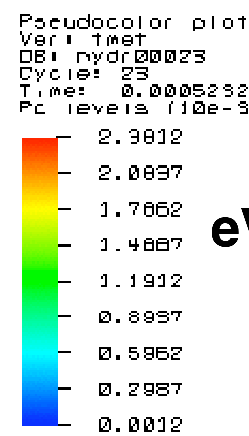


cm/μs

Scales from previous page (ρ and T)



g/cm3



eV

We have begun establishing target requirements for WDM studies and translating to requirements on the accelerator

We are quantitatively exploring the tradeoffs involved in focusing the beam in both space and time

We are using a state-of-the-art rad-hydro(HYDRA) simulation code to evaluate targets for WDM study. We are also comparing HYDRA with lower-dimensional codes, but using advanced EOS models

Several potential experiments are being considered including:

-- EOS/conductivity experiments on ETA-II
-- NDCX-I experiments heating condensed ices
-- Two-phase experiments on NDCX-II, IBX/NDC
-- Rayleigh-Taylor experiments on NDCX-II, IBX/NDC

Future simulations and calculations will simulate in detail many of these potential experiments

EXTRAS